

Neutrino Astronomy: A New Window to the Universe

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ABSTRACT

Neutrino astronomy offers the possibility to look into the interior of astrophysical objects. This advantage over the observation in classical astronomy in various regions of the electromagnetic spectrum goes along with a difficult detection of neutrinos. Pioneering experiments already have seen the sun and the supernova 1987A in the light of neutrinos. This offers the prospects to be able to look in the future into compact astrophysical objects which may be the sources of cosmic radiation.

INTRODUCTION

The disadvantage with "classical astronomies", such as the observation in the radio, infrared, optical, ultraviolet, X-ray or γ -ray regime is related to the fact that electromagnetic radiation is rapidly absorbed in matter and therefore only the surfaces of astronomical objects are visible. In addition, energetic γ -rays from distant sources are absorbed by γ - γ interactions with blackbody photons through the process

$$\gamma + \gamma \rightarrow e^+ + e^-.$$

The threshold energy for this process is around $E_\gamma = 10^{14}$ eV. Energetic photons from the Large Magellanic Cloud (LMC, distance 55 kpc) are already substantially absorbed by this process (Figure 1).

Charged primary cosmic rays could in principle also be used in astroparticle physics. The directional information, however, is only preserved for very energetic protons or nuclei, because at lower energies irregular magnetic fields randomize their arrival direction. On the other hand, energetic protons also interact with blackbody or starlight photons thereby degrading their energy. For protons of energies in excess of $5 \cdot 10^{19}$ eV the universe is no longer transparent.

The requirements for a good astronomy are:

1. particles (or radiation) must not be affected by regular or irregular magnetic fields.
2. particles must arrive at Earth. This excludes unstable particles, such as neutrons, unless their energy is extremely high.

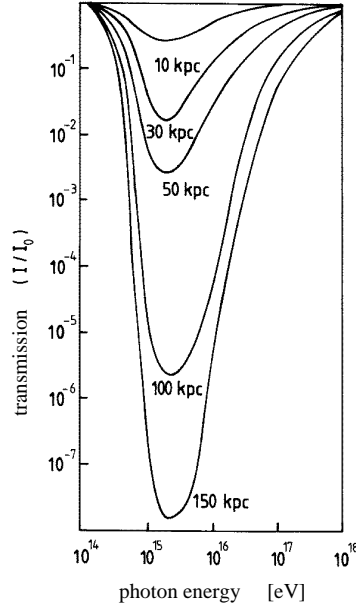


Figure 1: Fractional absorption of high energy γ -rays by the 2.7 K blackbody radiation for different cosmic distances [1, 2].

3. particle and antiparticle should be distinguishable. This excludes photons, because $\gamma = \bar{\gamma}$.
4. the particles must be penetrating to allow to look into the interior of stellar or galactic objects.
5. the particles should not be absorbed e.g. by blackbody photons.

Neutrinos fulfil all these requirements.

NEUTRINO BASICS

In the Standard Model of elektroweak interactions there are three families of quarks and leptons:

$$\begin{array}{lll}
 \text{quarks} & \begin{pmatrix} u \\ d \end{pmatrix} & \begin{pmatrix} c \\ s \end{pmatrix} & \begin{pmatrix} t \\ b \end{pmatrix} \\
 \\
 \text{leptons} & \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} & \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} & \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}
 \end{array}$$

The three neutrinos could have zero mass. Experimentally one can provide only mass limits [3]:

$$\begin{array}{ll} m_{\nu_e} \leq 4.5 \text{ eV} & \text{from } {}^3\text{H} - \text{decay} \\ m_{\nu_\mu} \leq 270 \text{ keV} & \text{from } \pi^+ \rightarrow \mu^+ + \nu_\mu \text{ decay} \\ m_{\nu_\tau} \leq 24 \text{ MeV} & \text{from } \tau^+ \rightarrow 3\pi^+ + 2\pi^- + \bar{\nu}_\tau \text{ decay} \end{array}$$

ATMOSPHERIC NEUTRINOS

For neutrino astronomy atmospheric neutrinos are an annoying background. However, for the study of interactions and in search for possible neutrino oscillations they may be interesting in their own right. A naïve expectation for the ν_μ/ν_e ratio for atmospheric neutrinos can be derived from their main sources

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu, & \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ \mu^+ &\rightarrow e^+ + \bar{\nu}_\mu + \nu_e, & \mu^- &\rightarrow e^- + \nu_\mu + \bar{\nu}_e. \end{aligned}$$

One would expect a ratio of

$$\frac{N(\nu_\mu, \bar{\nu}_\mu)}{N(\nu_e, \bar{\nu}_e)} = 2.$$

Some experiments find a deficit of muon-type neutrinos [4] and some do not [5]. In view of the difficult detection of low energy muon neutrinos one should be rather reluctant to propose new physics to explain a possible discrepancy.

SOLAR NEUTRINOS

The majority of neutrinos in the sun is produced in the proton-proton fusion reaction $p+p \rightarrow d + e^+ + \nu_e$ ("pp-neutrinos", 86%). About 14% originate from the electron capture process ${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$. A very small fraction (0.02%) of energetic neutrinos comes from the beta-decay of ${}^8\text{B}$: ${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e$. The total flux of neutrinos from the sun is about $7 \cdot 10^{10} \text{ cm}^{-2}\text{s}^{-1}$. The various sources contributing to solar neutrino spectrum are shown in Figure 2.

Also indicated in this diagram are the detection threshold energies in the various experiments looking for solar neutrinos. These experiments are [6, 7, 8]

1. Davis experiment: $\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$ ($E_\nu \geq 810 \text{ keV}$)
2. GALLEX and SAGE: $\nu_e + {}^{71}\text{Ga} \rightarrow e^- + {}^{71}\text{Ge}$ ($E_\nu \geq 233 \text{ keV}$)
3. Kamiokande: $\nu_e + e^- \rightarrow \nu_e + e^-$ ($E_\nu \geq 5 \text{ MeV}$)

In the first two cases of radiochemical experiments the minute number of produced ${}^{37}\text{Ar}$ or ${}^{71}\text{Ge}$ atoms has to be extracted in complicated chemical procedures and carefully counted. These integrating experiments provide no directional information, in contrast to the Kamiokande experiment, where the measured electron direction can be related to the position of the sun. The results of the different experiments are shown in Table 1.

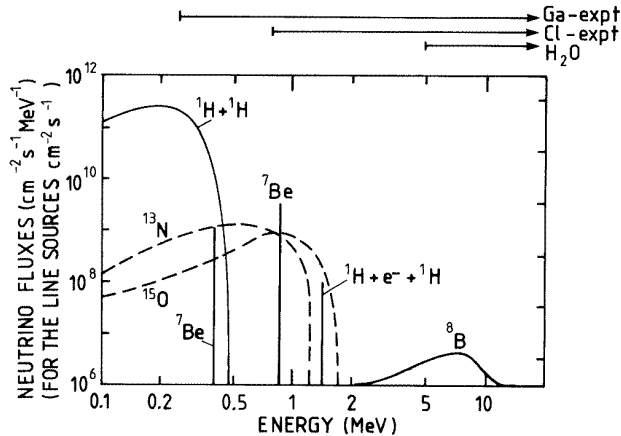


Figure 2: Theoretical differential energy spectra of electron neutrinos from nuclear reactions in the interior of the sun [6]. Also indicated are the threshold energies for neutrino detection in the Chlorine, Gallium and Water-Cherenkov experiments

Experiment	Results	Prediction	
		Bahcall	Turck-Chièze
Davis et al.	2.55 ± 0.25	8.0 ± 1.0	6.4 ± 1.4
Kamiokande	$(0.51 \pm 0.07) \times \text{predicted}$	1.0 ± 0.14	0.65 ± 0.07
SAGE	$73 \pm 18 \pm 7$	131.5 ± 7	122.5 ± 7
GALLEX	$76.7 \pm 8.4 \pm 4.9$	131.5 ± 7	122.5 ± 7

Table 1: Observed and predicted rates of neutrino fluxes [7, 9]. The Kamiokande result and the Turck-Chièze prediction are normalized to the Bahcall value.

For Davis et al., SAGE and GALLEX the rates are given in *solar neutrino units* (1 SNU = one capture per second per picobarn = neutrino flux \times cross-section $[10^{-36} \text{ s}^{-1}]$)

It appears that the "pp-neutrinos" are seen by SAGE and GALLEX and that there is a problem with the ^7Be and ^8B neutrinos. Many ideas have been put forward to solve the problem of missing solar neutrinos:

1. is the standard solar model correct? The flux of ^8B -neutrinos varies with the central temperature of the sun like T^{18} . A small decrease of this temperature could solve the ^8B -neutrino deficit. Turbulence of the solar material or observations in helioseismology indicate that the standard model may have to

be modified. A more exotic explanation could be provided by WIMPs which could have been trapped by the sun thereby lowering its core temperature [10].

2. the apparent deficit of ${}^7\text{Be}$ -neutrinos could be understood by an overestimated cross-section for ${}^7\text{Be}$ production in the sun at low energies.
3. a more exotic but very popular interpretation of the neutrino deficit (if it is real) could be provided by neutrino oscillations [6, 11, 12]. If the neutrinos were not massless they could oscillate from one neutrino flavour to the other. Since the solar neutrino detectors are only sensitive to ν_e , a maximal mixing could lead to equal amounts of ν_e , ν_μ and ν_τ at Earth and hence to a detection rate of only one third of the original neutrino flux from the interior of the sun. There are two varieties of neutrino mixing: one can have either neutrino-oscillation in vacuum or matter enhanced oscillations. The matter oscillations depend on the electron density in the sun. Somewhere inside the sun the electron density could be just right to induce resonant neutrino matter oscillations.
4. if neutrinos had a finite mass they could also have a magnetic moment. If their spin is flipped from the site of production to the detector on Earth they will not be seen because the neutrino detectors are insensitive to neutrinos with wrong helicity.

There are also more exotic explanations for the apparent solar neutrino deficit. I would prefer to check the points (1.) and (2.) before new phenomena are advocated.

SUPERNOVA NEUTRINOS

The star Sanduleak exploded in the Large Magellanic Cloud in 1987. In supernova explosions vast numbers of neutrinos are emitted. There are two sources of neutrinos: the first comes from the deleptonization process $p + e^- \rightarrow \nu_e + n$ when the neutron star is formed, the second source are thermal neutrinos which are produced at temperatures of around 10 MeV through the chain

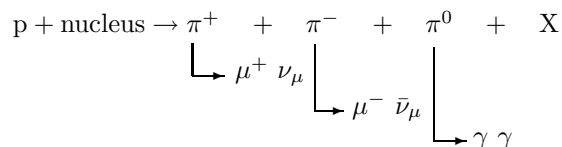
$$\begin{aligned}\gamma + N &\rightarrow e^+ + e^- + \tilde{N} \\ e^+ + e^- &\rightarrow Z \rightarrow \nu_x + \bar{\nu}_x \quad x = e, \mu, \tau \quad .\end{aligned}$$

Two experiments (Kamiokande and IMB) have detected neutrinos from SN 1987A. The IMB-experiment saw 8 events (threshold ≥ 19 MeV) while Kamiokande saw 12 events (threshold ≥ 5 MeV) [8]. Mainly $\bar{\nu}_e$'s were detected via the charged current process $\bar{\nu}_e + p \rightarrow n + e^+$. The total energy emitted in the form of neutrinos was estimated to be $E_{\text{total}} = (6 \pm 2) \cdot 10^{46}$ J corresponding to a total

neutrino flux of $\sim 10^{58}$ emitted over a time of ~ 10 seconds. From the fact that the supernova neutrinos arrived at Earth a limit for the neutrino lifetime could be derived, and the observed time dispersion at Earth was used to infer an upper limit on the electron neutrino mass of $m_{\nu_e} \leq 10 \text{ eV}$.

GALACTIC AND EXTRAGALACTIC NEUTRINOS

The most popular acceleration and production mechanism of energetic galactic or extragalactic neutrinos is from binaries consisting of a "target" star which is orbited by a "production" pulsar. The pulsar accelerates protons which interact in the stellar atmosphere of the companion star according to



providing equal amounts of neutrinos and γ -rays. The photon yield, however, strongly depends on the pulsar phase and the interplay of the local density and the column density of the stellar atmosphere [13]. But also more unorthodox production mechanisms involving cosmic strings are proposed [14].

In these models particles are created at ultrahigh energies (10^{24} eV) by the decay of massive X-particles associated with new fundamental unified interactions near the grand unification (GUT) scale. Such gauge theories predict phase transitions in the early universe which are expected to create topological defects, such as e.g. cosmic strings. These cosmic strings could possibly release X-particles due to collapse or annihilation processes [14]. In GUT-theories the X-particles are predicted to decay into jets of hadrons, which would eventually provide copious numbers of γ -rays and neutrinos. Figure 3 shows expectations for the differential fluxes of γ -rays, neutrinos, protons and neutrons based on the cosmic string origin [14]. The fluxes have been estimated for spatial uniform injection; i.e. the particles were propagated through extragalactic space, and the fluxes were normalized to the observed particle rate at 10^{20} eV . Figure 3 also shows experimental data from AGASA and the Fly's Eye experiment (dots with error bars), piecewise power law fits to the observed charged cosmic ray rate and experimental upper limits on the γ -ray flux ([14] and references therein).

For neutrino detectors under construction (DUMAND, AMANDA, NESTOR) the minimum detectable flux for neutrinos in the TeV region is of the order of $10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$ [15, 16, 17]. This limit could possibly be somewhat pessimistic if one assumes that the neutrino nucleon cross-section rises substantially at large energies due to the abundance of low energy partons inside the nucleon [18]. Candidate sources which might fulfil the minimum flux requirement are VELA X1, CRAB, Cyg X3, Cen A, Markarian 421 and the quasar 3C273. Also all binary pulsars, supernova shells, active galactic nuclei and the galactic center are possible candidates. Up to now, however, no point source emitting high energy neutrinos has been detected.

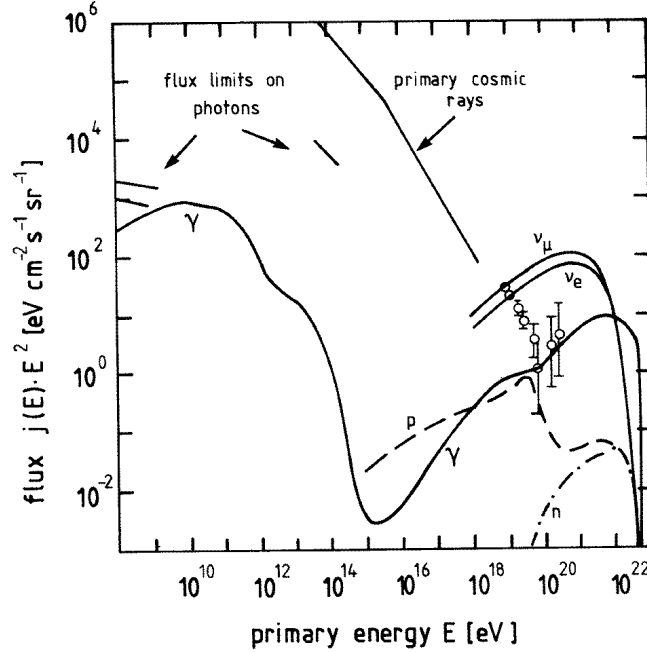


Figure 3: Predictions for the differential fluxes of γ -rays, neutrinos, protons and neutrons from the collapse or annihilation of topological defects, such as cosmic strings via the decay of GUT X-particles along with experimental data on charged cosmic ray rates and upper limits on γ -ray fluxes ([14] and references therein).

CONCLUSION

Atmospheric neutrinos seem to be well under control. The discrepancy between the predicted and actually measured number of solar neutrinos can probably be understood by minor modifications to the standard solar model and by use of improved measurements of nuclear processes relevant for neutrino production in the solar core. The supernova neutrinos are in excellent shape. Energetic galactic or extragalactic neutrinos have not been seen yet. Ongoing accelerator experiments will answer the question whether neutrino oscillations are a reality.

ACKNOWLEDGEMENTS

I am grateful for the hospitality and support provided by the summer school organizers. My special thanks go to Janusz Kempa, Jerzy Wdowczyk and Wiesław Tkaczyk. I thank also Volker Schreiber and Detlev Maier for their help in preparing

the written version of my talk.

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